NET II SIMULATION OF A PULSE FORMING LINE (PFL) WITH SPARK GAP AND LOAD

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Abstract

The purpose of this Net II [1] simulation is to understand the operation of a spark gap switch in series with a resistive liquid load at the output of a pulse forming line (PFL), fed by a specified power supply. A series of runs simulated a shorted spark gap at the output of a PFL fed by a Marx generator. Comparing results with experimental data, it was inferred that the load resistance is less than the PFL's impedance, and with considerable inductance. We seek a load inductance as close to zero as possible.

Another series of Net II runs included a switch in the load circuit, set to close when the first voltage peak is across it. Runs were executed with and without a diode in the Marx generator output. In the ideal case, matched load and zero inductance, and with the diode, a flat-top pulse appeared, as expected. Inductance in the output smeared out the pulse, and caused oscillations following the pulse, even with the diode.

Introduction

For some time there has been a need for a high-repetition rate (10 Khz) high-power switch. One step in achieving this goal is to obtain a quantitative understanding of the operation of a spark gap switch in series with a resistive liquid load at the output of a pulse forming line (PFL). The purpose of the work reported here is to describe a way of achieving such an understanding. The results of a study to quantify what is needed to obtain a clean square pulse across the switch and load from the PFL will be reported. Finally, we take a brief look at a lossy switch model, comparing Net II output with experimental results.

Description of Work

Most of the work reported here is with a PFL whose characteristic impedance is 0.86 ohm, with a round-trip transit time of 200 ns. A diagram of the basic circuit is shown in Figure 1. The directions of the PFL input current I_a and PFL output current I_b, shown in Figure 1, are conventions assumed by Net II. At time t=0, switch S1 is closed, and switch S2 is open. Switch S3 represents the spark gap at the output of the PFL, L_2 represents its inductance, and R_L is the resistance of the liquid load. The elements C_1, L_1, and R_1 represent a Marx generator circuit with C_1 being the erected capacitance. In the first results to be presented, S1 opens at t=0.9 μsec and S2 closes at t=1.0 μsec.

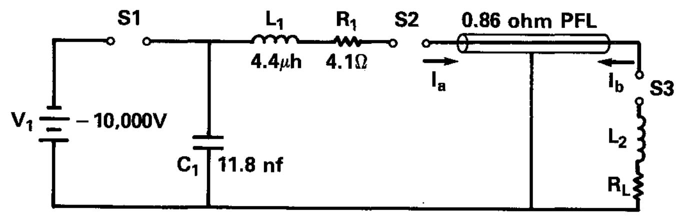

FIGURE 1. BASIC CIRCUIT DIAGRAM

Shorted Spark Gap

The first Net II runs were executed for a shorted spark gap, (S3 of Figure 1 closed). Figure 2 shows a computer plot of the output current I_b from the PFL with load resistance R_L=0.86 ohm (matched to the PFL) and the inductance of the spark gap L_2=0. The input current I_a is a replica of I_b. The large oscillations are between the erected capacitance C_1 and output inductance L_1 of the Marx generator. Experimental results showed the first output current peak I_{bm} to be 1.4 times the first input current peak I_{am}. That is, $|I_{bm}|/|I_{am}|$=1.4. Net II results showed these peaks to be equal.

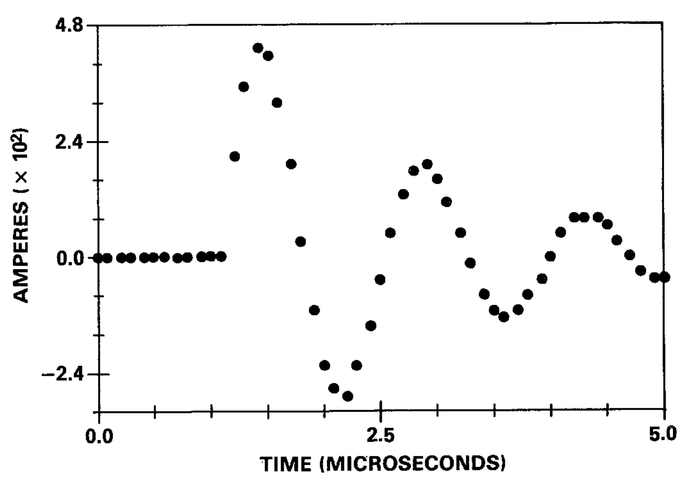

FIGURE 2. OUTPUT CURRENT I_b FROM PFL; SHORTED SPARK GAP: R_L = 0.86 ohm, L_2 = 0

The liquid load resistance (a soap solution) had been measured at 60 Hz to be 0.86 ohm. As a spark gap load, it is under high voltage transient oscillations. Under these conditions its resistance is difficult to measure directly. A series of Net II runs was executed with different load resistance R_L and spark gap inductance L_2, and the $|I_{bm}|/|I_{am}|$ ratio for the first peaks noted. The combinations of R_L and L_2 and resulting ratios are shown in Table I.

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14. ABSTRACT
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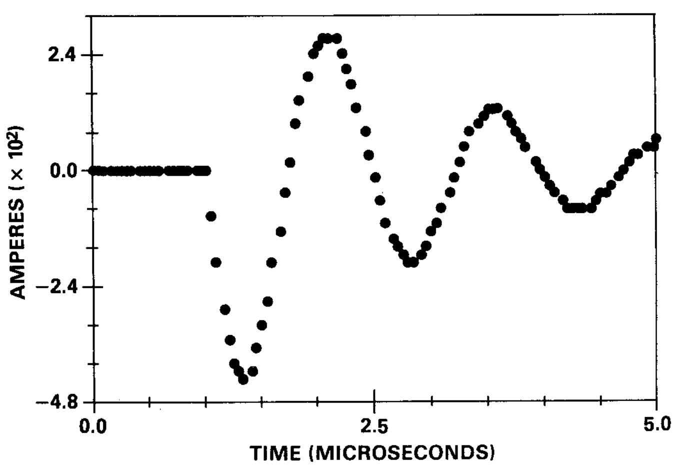
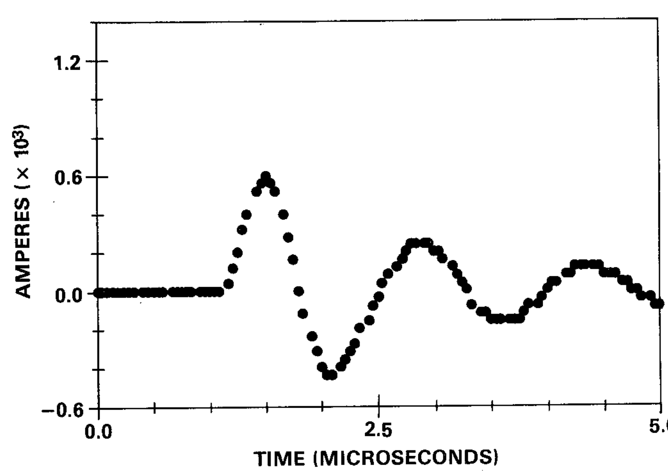
TABLE I. $|I_{bm}|/|I_{am}|$ for Various R_L and L_2; Shorted Spark Gap

L_2(nh) / R_L(ohm)	10	50	100	200	500
0.1	1.52	1.69	1.75	1.75	1.47
0.4	1.22	1.38	1.46	1.50	1.32
0.5	1.15	1.31	1.39	1.44	1.28
0.7	1.07	1.19	1.26	1.32	1.20

The simulation most resembling experimental results had R_L = 0.5 ohm and L_2 = 100nh. Computer plots for I_a and I_b for this run are shown in Figure 3. By matching experimental data with Net II simulations, an indirect method for determining the load resistance R_L is possible. This will be useful in verifying results of a method, now being devised, for measuring the liquid load resistance directly under transient, high-voltage conditions. Also, this simulation can yield a quantitative look at how much spark gap inductance L_2 can be tolerated without unacceptable distortion of the output waveform.



a. INPUT CURRENT I_a TO PFL



b. OUTPUT CURRENT I_b FROM PFL

FIGURE 3. SHORTED SPARK GAP; R_L = 0.5 ohm, L_2 = 100 nh

Spark Gap Operating

The next series of Net II runs is with the output spark gap (S3) operating: Set to be open and to close when the first high-voltage peak is across it. The following four runs were executed: R_L = 0.5 ohm, L_2 = 100 nh; R_L = 0.86 ohm, L_2 = 100 nh; R_L = 0.5 ohm, L_2 = 200 nh; R_L = 0.86 ohm, L_2 = 200 nh. A computer plot of I_b for R_L = 0.5 ohm, L_2 = 100 nh is shown in Figure 4. The input current I_a has the same waveform as that shown in Figure 3a, but with slightly diminished amplitude. The output current I_b shows a tall peak, followed by oscillations caused by the output circuitry of the Marx generator, and by a mismatch between the PFL and the inductive load.

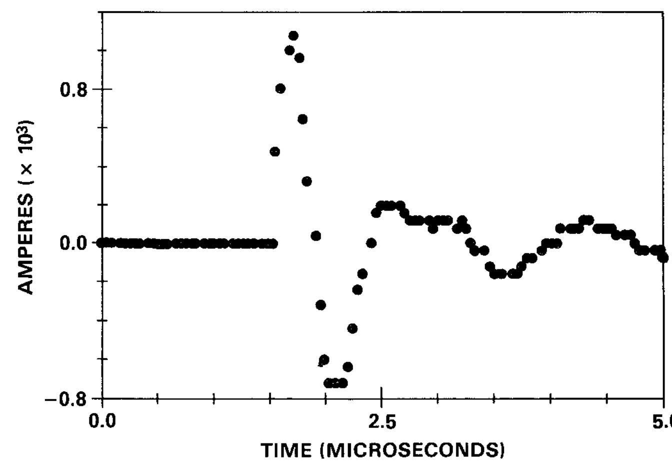


FIGURE 4. OUTPUT CURRENT I_b FROM PFL; SPARK GAP OPERATING; R_L = 0.5 ohm, L_2 = 100 nh

Diode in Marx Generator Output

In an attempt to stop the oscillations in the output load, Net II simulations were run with a diode in the output of the Marx generator. Figure 5 shows a circuit diagram with the diode. Runs with the same combinations of L_2 and R_L noted above were executed. Illustrated in Figure 6 are computer plots of I_a and I_b for R_L = 0.5 ohm and L_2 = 100 nh. This time, I_a is a simple pulse which charges the PFL. Oscillations from the Marx generator are eliminated. The output current I_b shows a tall pulse, followed by smaller oscillations than before. These oscillations are due to mismatch between the PFL impedance and load. As expected,

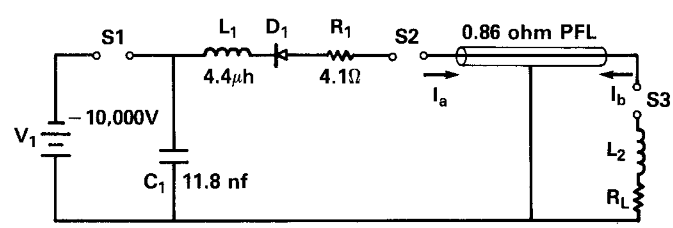
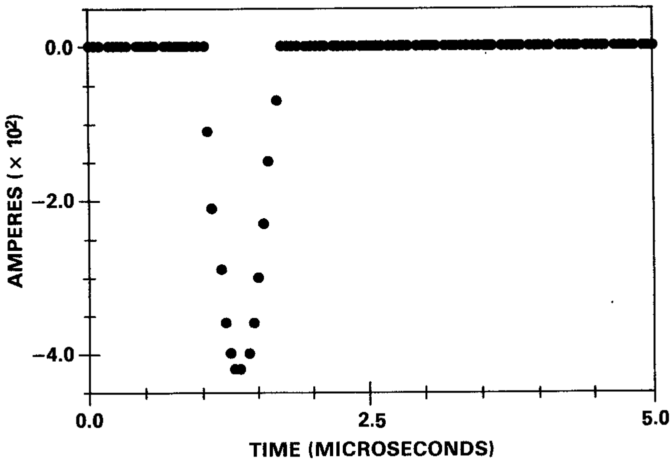
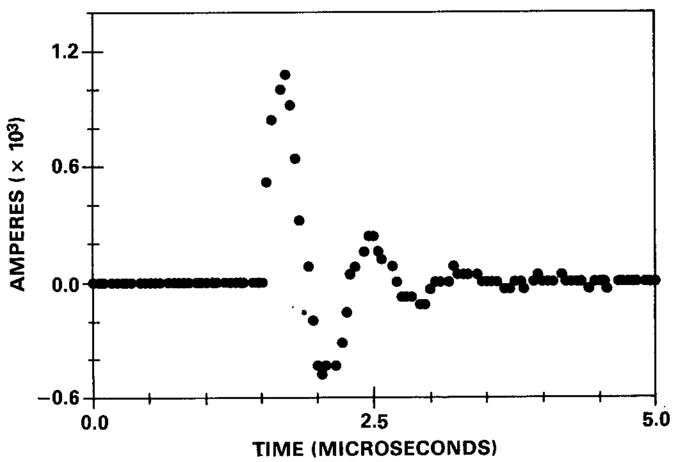


FIGURE 5. BASIC CIRCUIT DIAGRAM WITH DIODE IN MARX GENERATOR OUTPUT



a. INPUT CURRENT I_a TO PFL



b. OUTPUT CURRENT I_b FROM PFL

FIGURE 6. SPARK GAP OPERATING; DIODE IN MARX GENERATOR OUTPUT; R_L = 0.5 ohm, L_2 = 100 nh

the larger the spark gap inductance L_2, the greater in amplitude are these oscillations.

Using the same circuit of Figure 5, a run for the ideal case, with R_L = 0.86 ohm and L_2 = 0, was executed. A computer plot of I_b is shown in Figure 7. Output current I_b is expected to be a flat-top pulse of 200 ns duration. Figure 7 shows a slightly rounded top of the pulse, and a value of I_b slightly greater than zero at the end of the pulse. This is caused by roundoff errors due to discontinuous jumps in I_b and the fact that the PFL was approximated by finite elements. Input current I_a remains unchanged. This is the desired output waveform. It would be fairly easy to adjust R_L to 0.86 ohm. Lowering L_2 below 100 nh may be a difficult challenge. It could perhaps be accomplished by redesigning the spark gap housing. About the best we can hope for is a somewhat distorted square pulse, followed by small oscillations due to load mismatch caused by unwanted spark gap inductance.

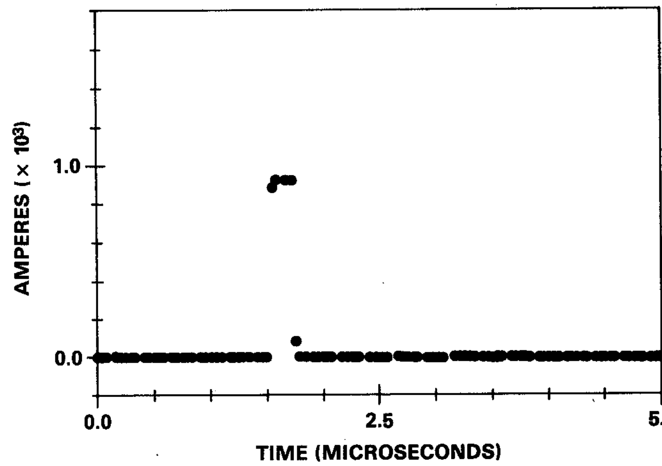


FIGURE 7. OUTPUT CURRENT I_b FROM PFL; SPARK GAP OPERATING; DIODE IN MARX GENERATOR OUTPUT; R_L = 0.86 ohm, L_2 = 0

A First Look at Gap Losses

The PFL here is a 50 ohm, 300 ns line. A diagram is shown in Figure 8. Resistor R_1 is the charging resistor, which prevents a heavy current drain on the power supply when the line discharges. Resistor R_L is fixed at 0.01 ohm, and is needed by Net II for monitoring load current. It has been observed in the laboratory that the envelope of the oscillating current through a lossy spark gap, fed by an underdamped RLC circuit, decays linearly. This suggests a constant voltage across the gap regardless

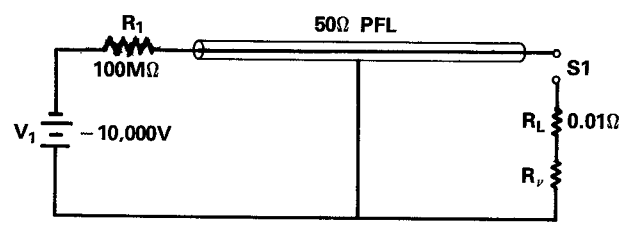


FIGURE 8. PFL WITH LOSSY SPARK GAP MODEL

of the current magnitude. To simulate this condition, we create a fictitious variable resistance R_V , expressed as

$$R_V = \frac{V}{|I(R_L)| + \delta} \tag{1}$$

where V is the constant voltage across R_V, and I (R_L) is the current through the spark gap. The purpose of the constant δ is to prevent R_V from becoming excessively large because of attempting to divide by zero, since I (R_L) goes through zero each half cycle. Constant δ was set at 1.0, which is small compared with the maximum current, but yet allows smooth Net II operation. At

time t=0, switch S1 is open, set to close at t=0.1 microsecond. Runs were performed with V=50, 100 and 200 volts. The solution most resenbling experimental results was for V=100 volts.

Figure 9 shows a computer plot of I_b vs time. Figure 10 shows the result for a 1 mm spark gap at atmospheric pressure, whose breakdown voltage was 7kV. Comparison of figures 9 and 10 indicated that the voltage across a fully conducting gap is essentially constant. Its value depends on many factors, among which are gap spacing, the gas involved, temperature, pressure, etc.

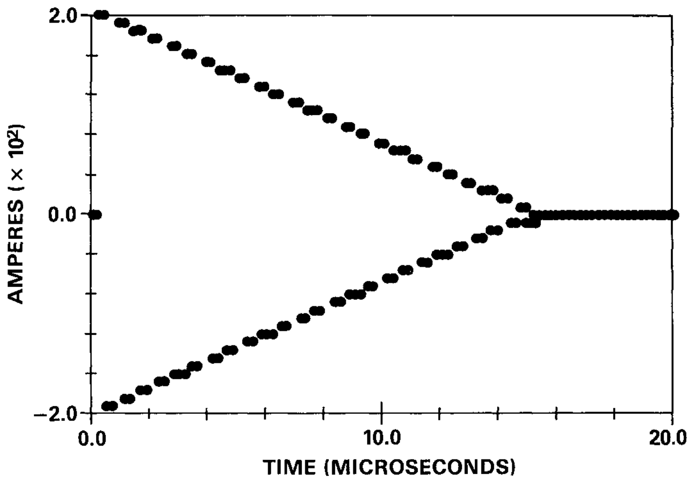


FIGURE 9. OUTPUT CURRENT FROM PFL WITH LOSSY SPARK GAP MODEL

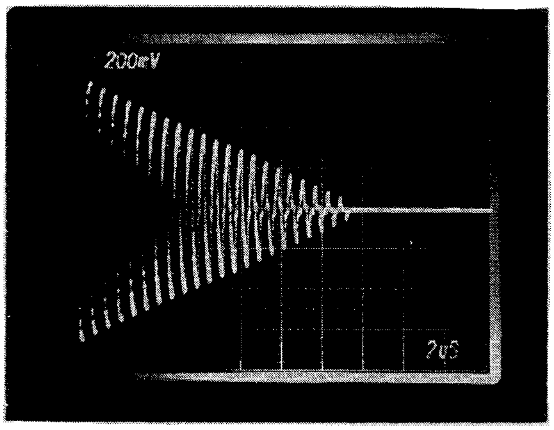


FIGURE 10. 1 mm SPARK GAP IN AIR 7 kV BREAKDOWN

Conclusion

A series of Net II runs with different PFL-spark gap circuits has been reported. With a shorted gap there are large oscillations across the load, caused by resonance in the output circuit of the Marx generator feeding the circuit. Net II provides an indirect method for estimating the actual load resistance and spark gap inductance, based on comparison of the amplitudes of the oscillating currents at the input and output of the PFL.

When the load switch closes at the first peak from the Marx generator, a tall distorted pulse from the PFL, followed by oscillations, results across the load. A blocking diode in the Marx output eliminates most, but not all these oscillations. The remaining oscillations are from load mismatch. A blocking diode in the Marx output would be a great help in reducing unwanted oscillations, but it will be difficult to find a diode that would withstand the large currents and voltages involved. With a diode in the Marx output, Net II allows us to determine how the PFL pulse is degraded by spark gap inductance. It is believed that the spark gap inductance can be brought down to 100 nh fairly easily. Lowering it further may take a greater effort with uncertain results.

Using a resistively-charged PFL, Net II was applied to an empirical lossy spark gap model for the first time. Results agreed qualitatively with experimental results. A more detailed switch loss study, using this and other models, is recommended.

Another recommendation is to experiment with different resistive load liquids besides soap. Since the soap load is sensitive to temperature, it would be helpful to find a liquid load that is less sensitive.

References

[1] Allan P. Malmberg, Net-2 Network Analysis Program, The BDM Corporation prepared for Harry Diamond Laboratories, Contract No. DAAG39-70-C-0050, September 1973.

[2] David B. Cummings, Pulsed Power Ignitron Switches, Power Conditioning Handbook, edited by W. J. Sarjeant and James O'Laughlin; Van Nostrand Rheinhold, to be published.